# Effects of Space Weather on Ionospheric Irregularities: from Measurements and Understanding to Prediction

**Xiaoqing Pi**

***Jet Propulsion Laboratory, California Institute of Technology***

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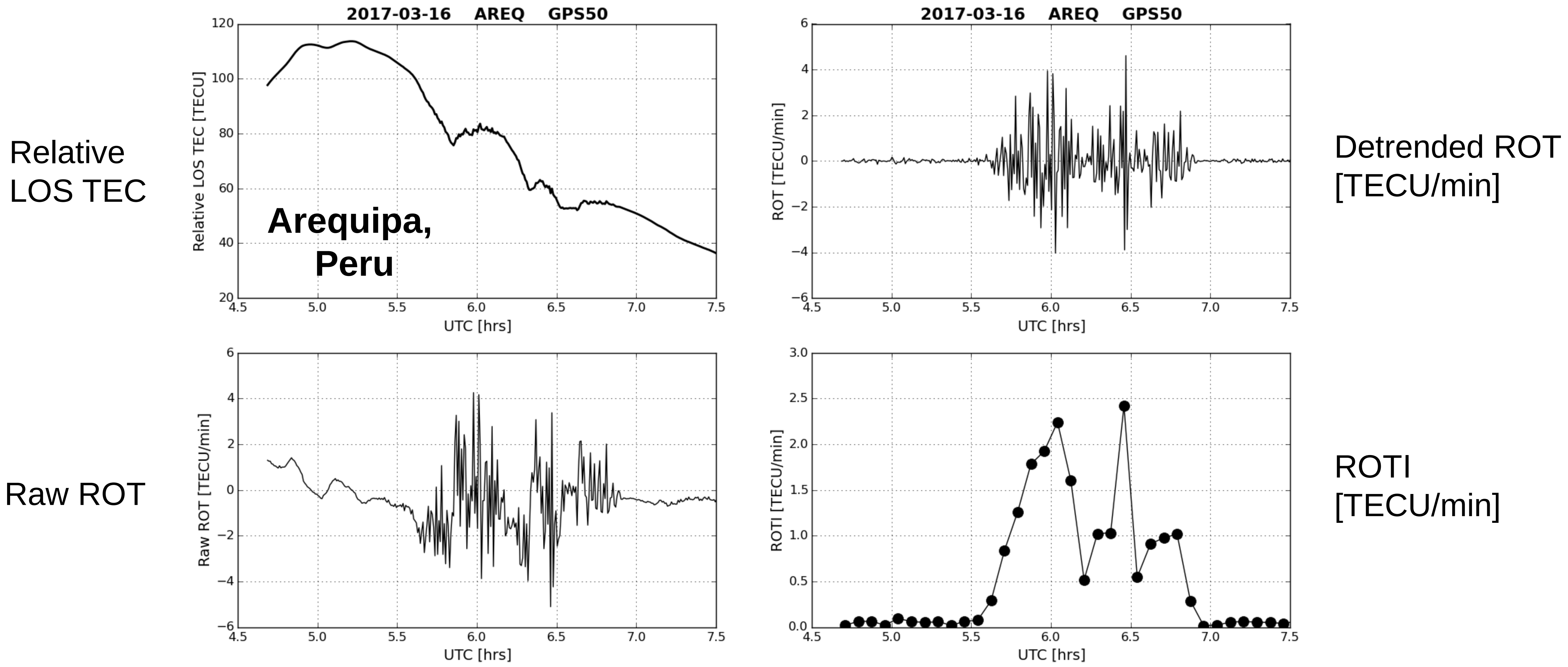
# Outline

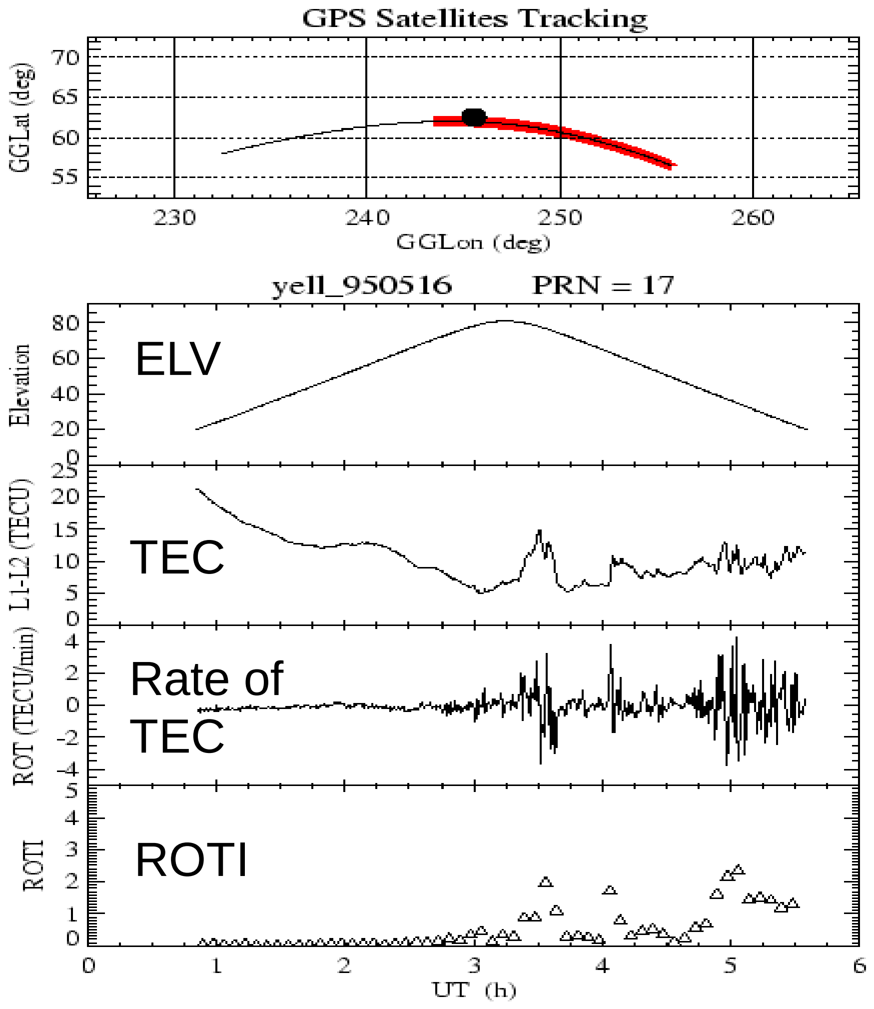
- **Measurements of ionospheric irregularities and scintillation using Global Navigation Satellite System (GNSS) signals**
  - ✓ ROTI vs. $S_4$ and $\sigma_\phi$
  - ✓ Global Map of Ionospheric Irregularities (GMII)
- **Effects of ionospheric scintillation on GNSS and synthetic aperture radar (SAR) applications**
- **Effects of space weather on ionospheric irregularities**
  - ✓ Polar regions
  - ✓ Sub-auroral and mid-latitude regions
  - ✓ Low latitudes
- **Assimilative modeling of large-scale ambient ionospheric variations that indicate the dynamical effects of space weather events**
  - ✓ Relationship between small-scale irregularities and large-scale variations
- **A path to prediction of occurrence of ionospheric irregularities**

# Low-Latitude (Arequipa, Peru) Ionospheric Irregularities Measured Using Geodetic-Type GPS Receivers

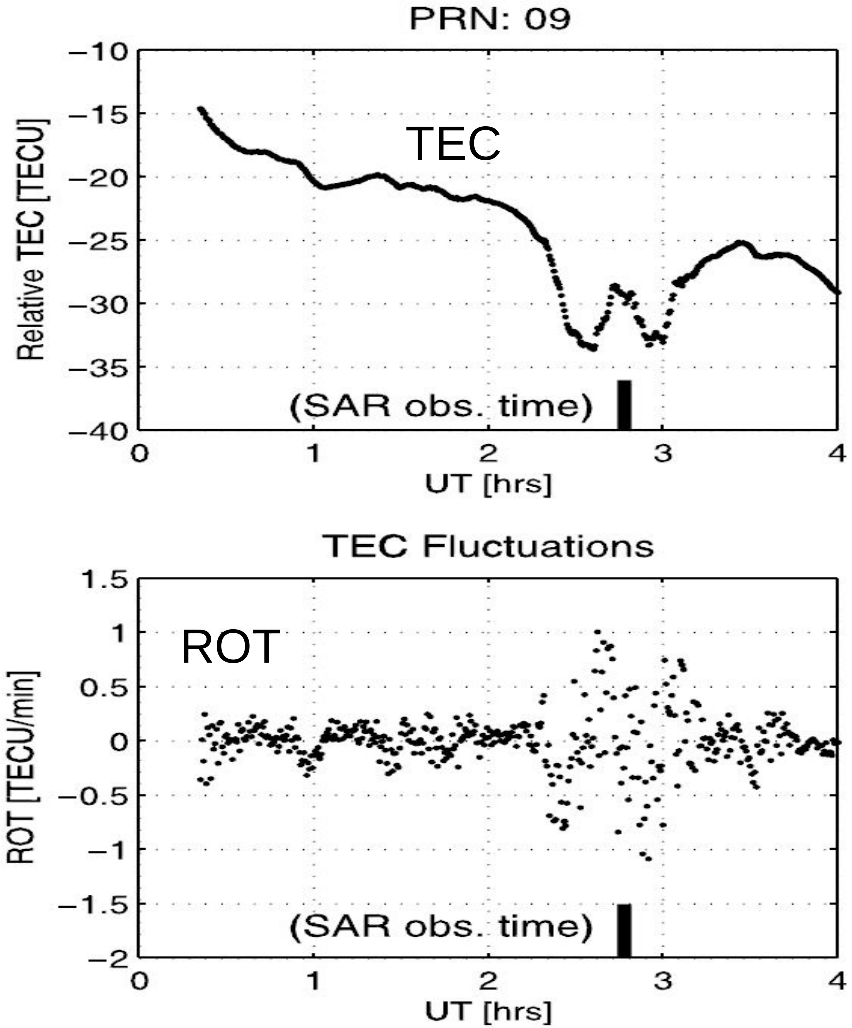



**Scale size of irregularities: a few tens kilometers**

# ROTI: Measurement of Ionospheric Irregularities Using Geodetic-Type GPS Receivers




**Polar Region (Canada)**




**Low Latitude (Brazil)**

# Ionospheric Scintillation & Irregularity Indices

$$S_4(f) = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \propto f^{-\alpha}$$

$$\sigma_\phi(f) = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2} \propto f^{-1}$$

$$\mathrm{ROT} = C\,\frac{\Phi_I(t+\Delta t) - \Phi_I(t)}{\Delta t}$$

$$\mathrm{ROTI} = \sqrt{\langle \mathrm{ROT}^2 \rangle - \langle \mathrm{ROT} \rangle^2}$$

## $S_4$ – amplitude scintillation index

## $\sigma_\phi$ – phase scintillation index

- Frequency-dependent indices
- Covering the effects of irregularities at smaller scales (data at high sampling rate, 50 or 100 Hz)
- Measurements of phase scintillation require high-quality local oscillators in the receiver

## ROTI – Rate of TEC index

- Independent of radio frequency
- ROT sampled at $\Delta t$ from 30 sec to 1 sec, losing smaller-scale samples
- Not susceptible to local oscillator errors
- > $10^3$ stations globally!

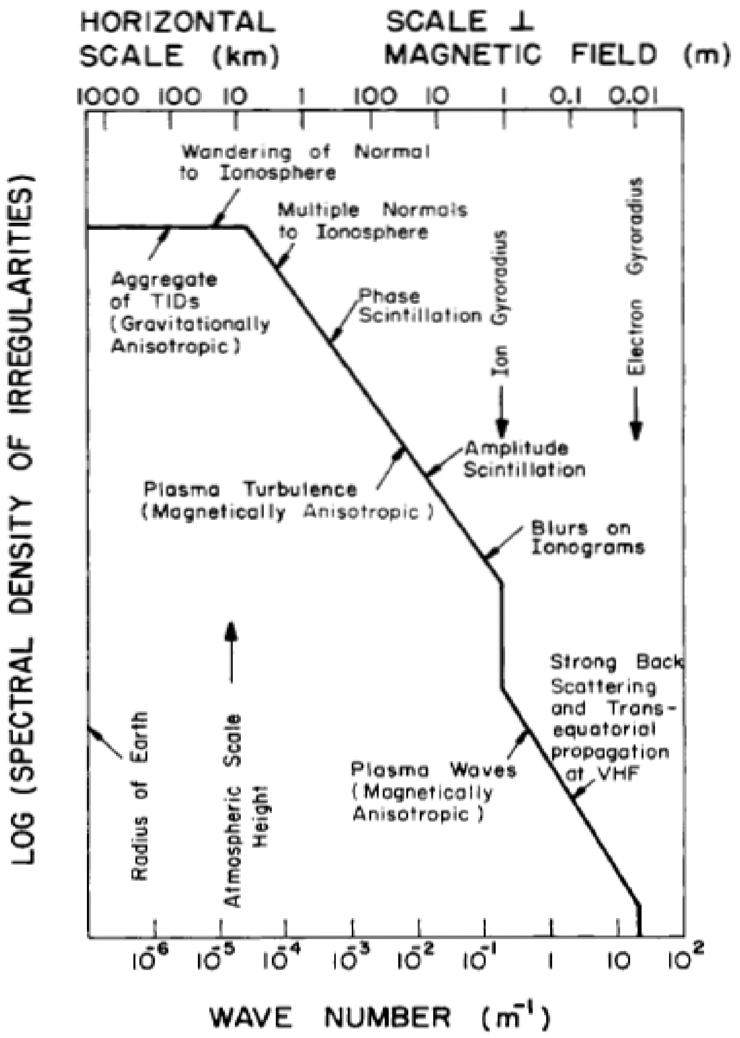
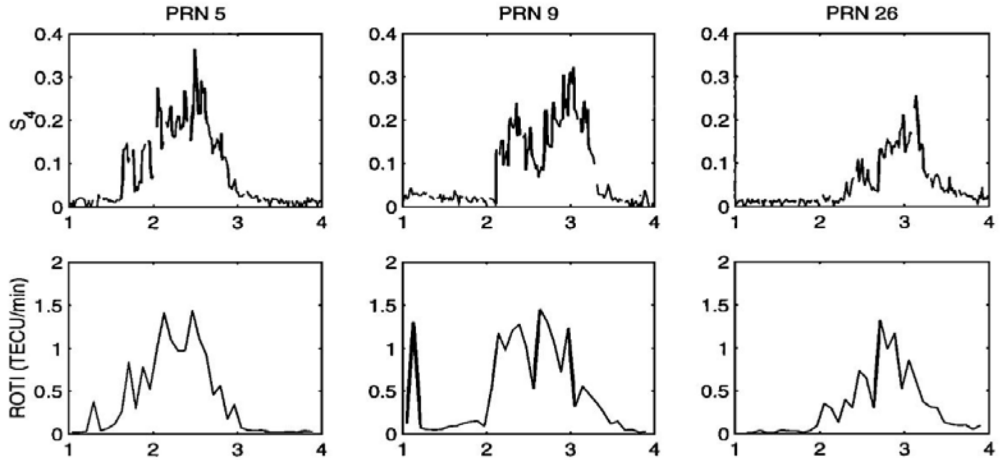



Fig. 5. A composite spectrum summarizing intensity of ionospheric irregularities as a function of wavenumber over a spatial scale from the electron gyro-radius to the radius of earth. (After Booker [46].)

# Relationship between ROTI, $S_4$ and $\sigma_\phi$:
# Occurrence Related, but Magnitude Complicated!

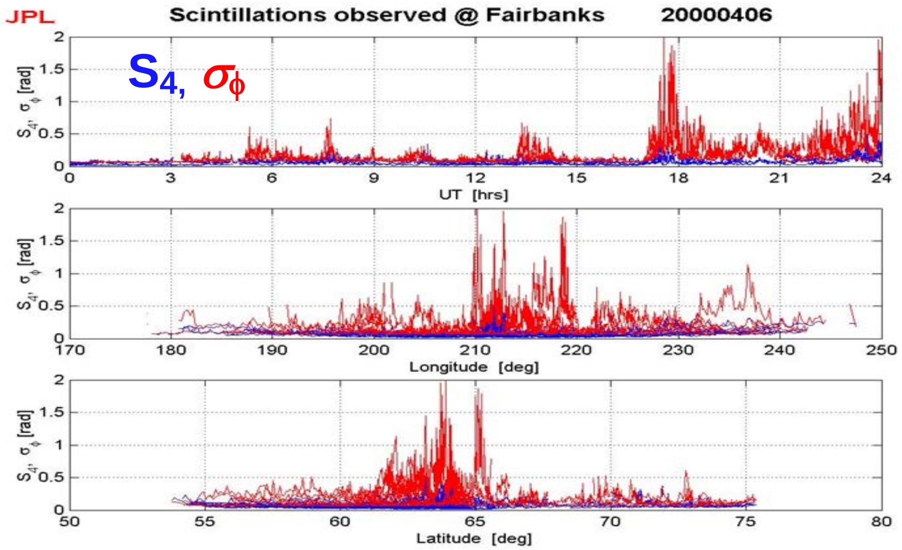
[Beach and Kintner, 1999]

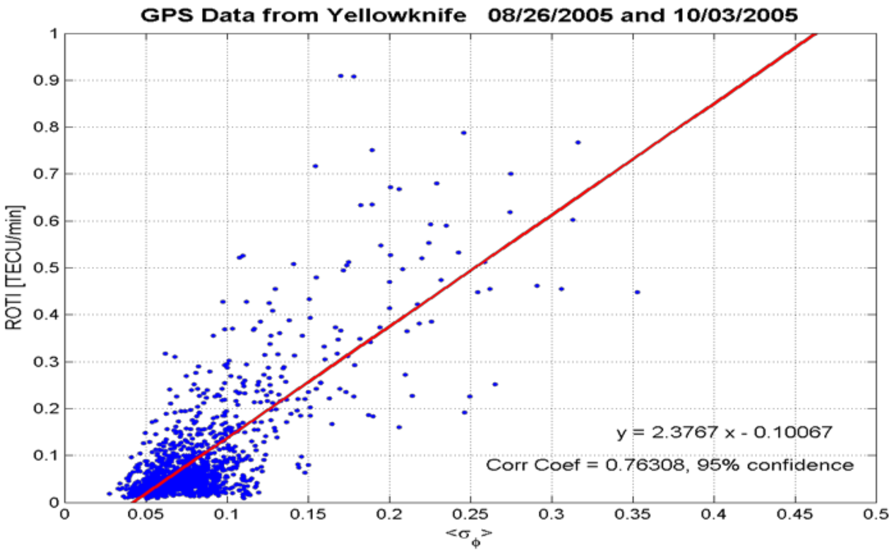



- Low latitudes
  - ➢ Occurrence is correlated
- High latitudes
  - ➢ ROTI and $\sigma_\phi$ correlated in occurrence, but not necessarily in magnitude
  - ➢ $S_4$ may not be correlated with $\sigma_\phi$ and ROTI
- Middle latitudes
  - ➢ Can occur during some storms, but not well studied

[Pi et al., 2004]

Auroral Zone

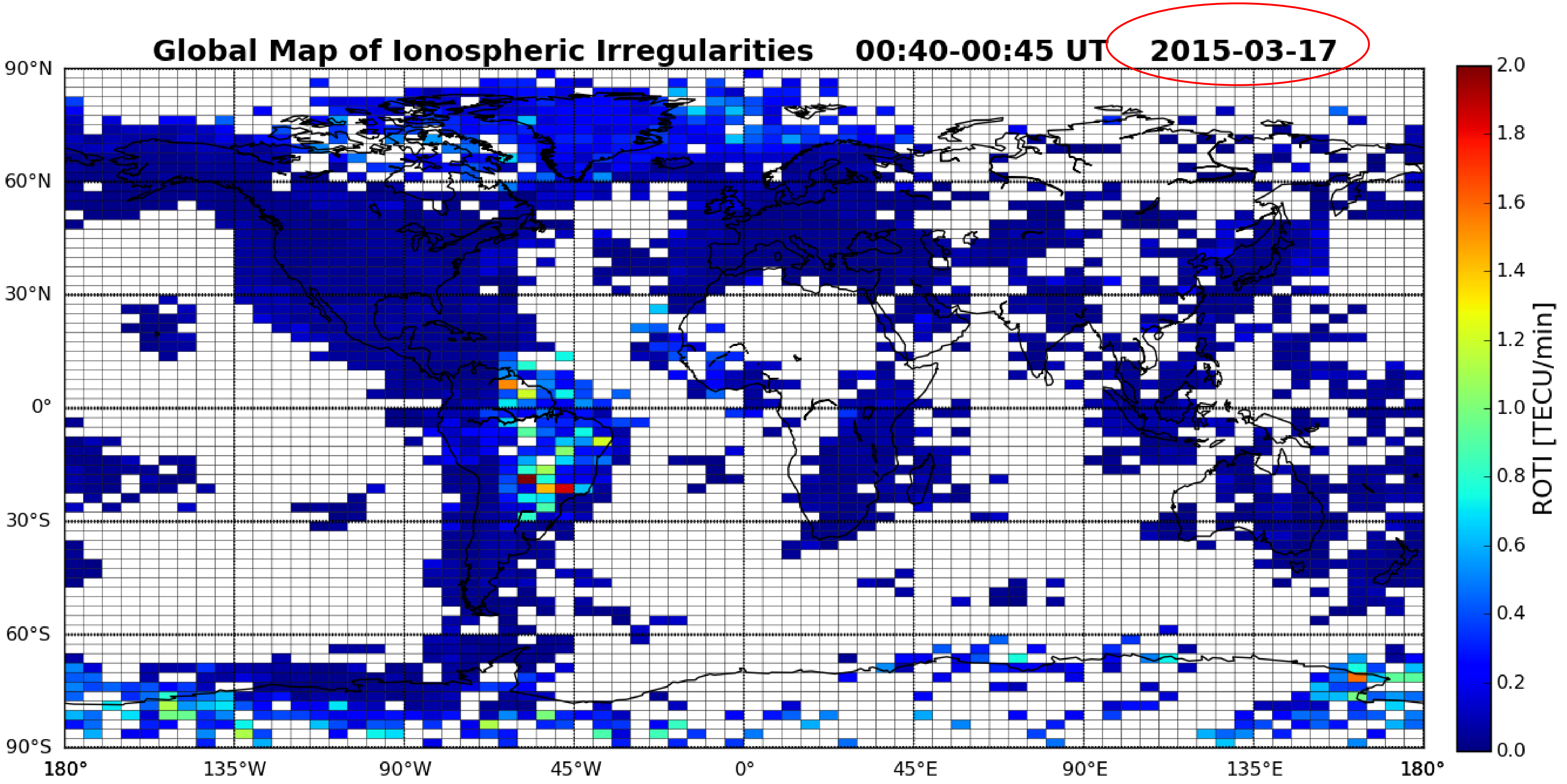



[Pi et al., 2013]

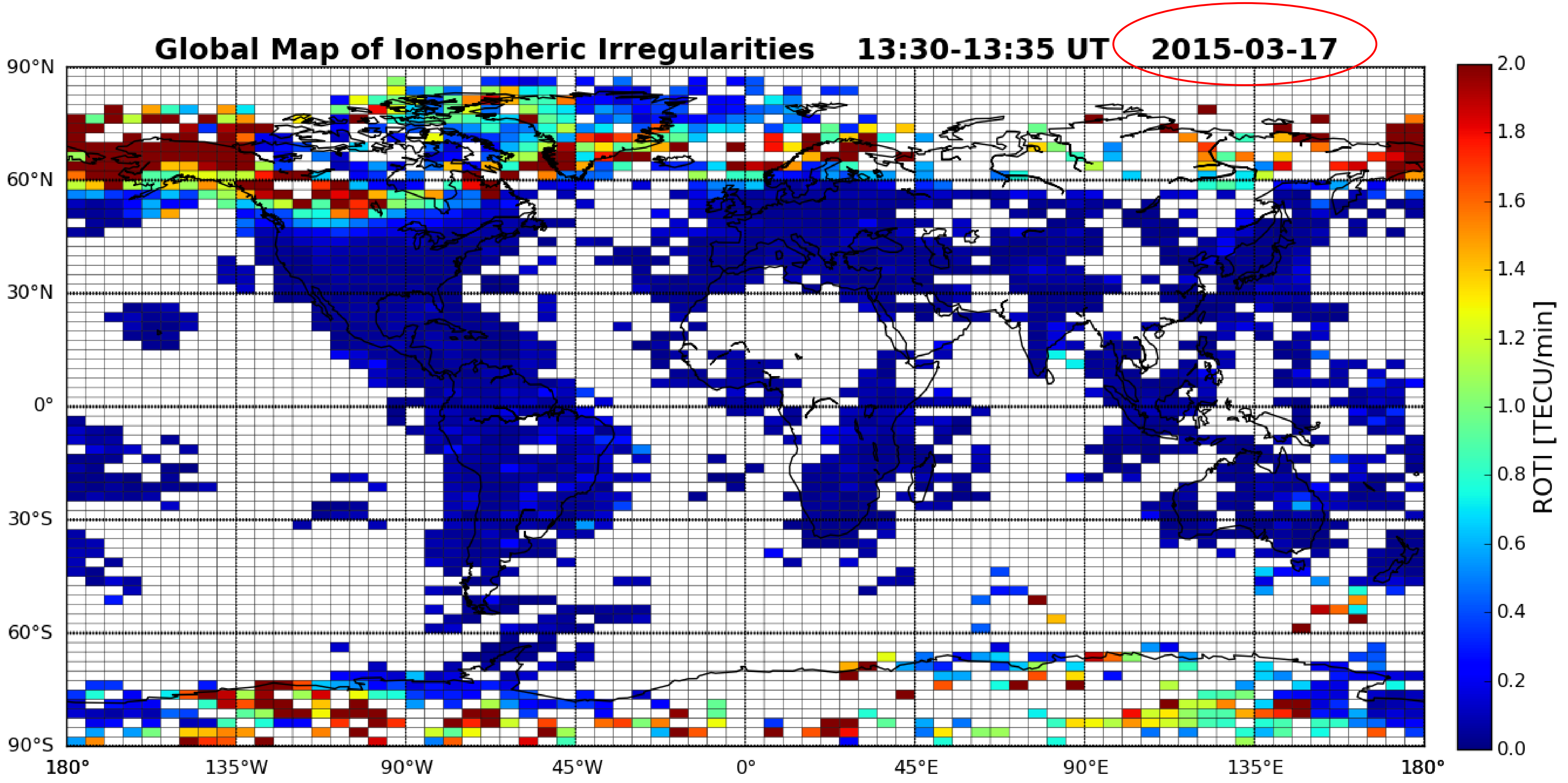
Auroral Zone

# Global Map of Ionospheric Irregularities(GMII) under Nominal Conditions: Low-Latitude Irregularities

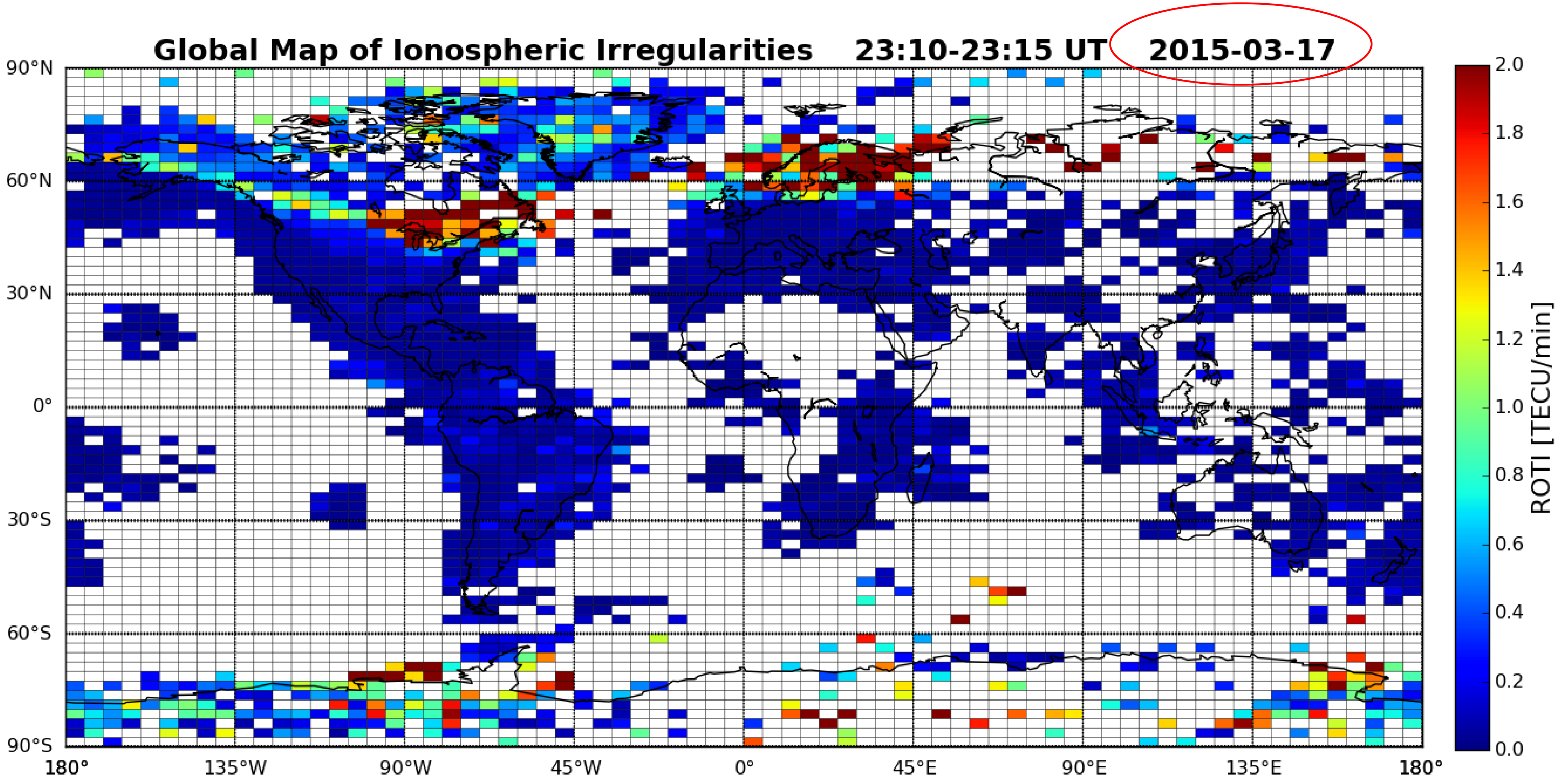


# Irregularities in the Auroral Zone

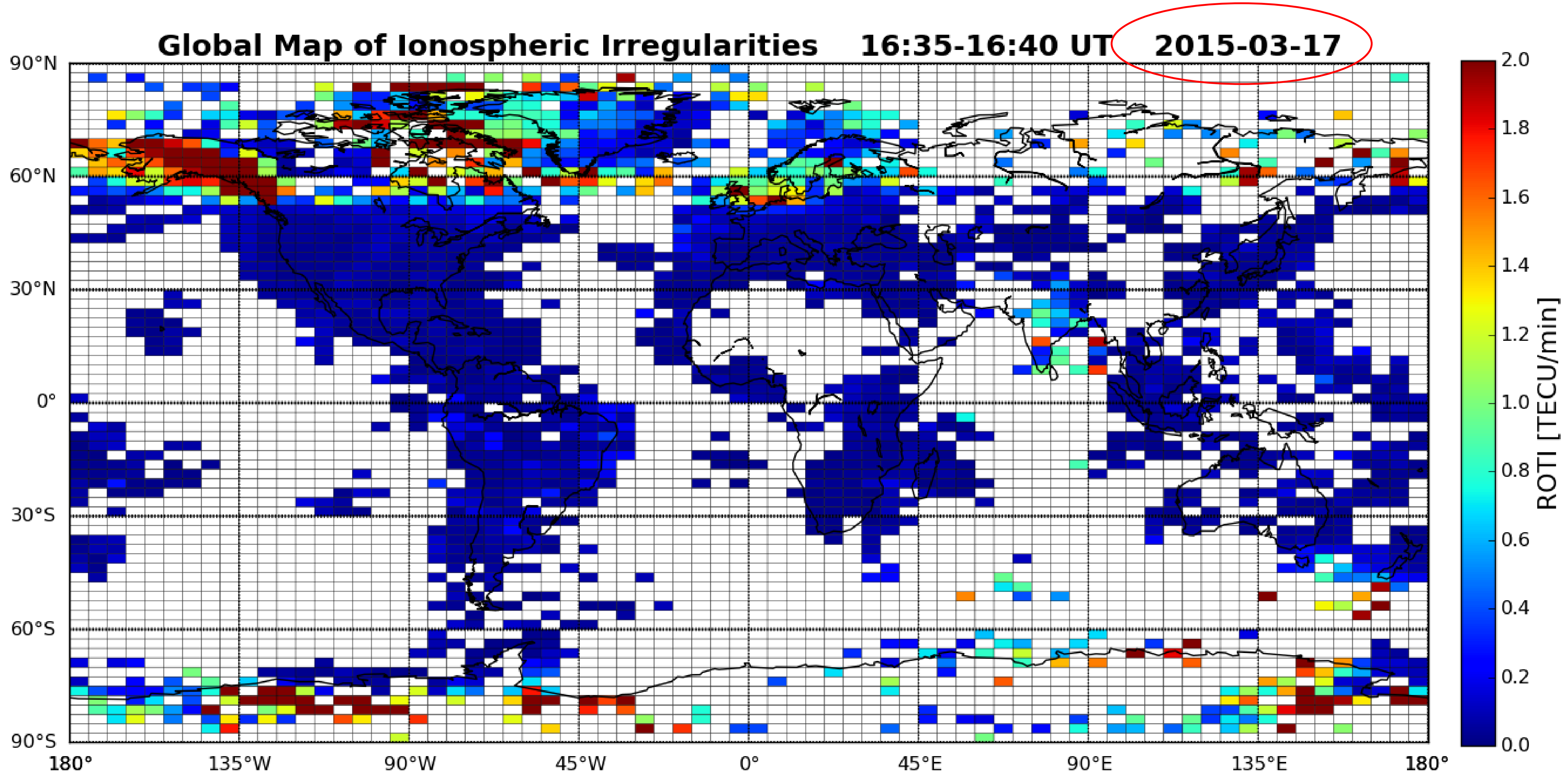
## During Intense Auroral Electrojet Events (17 March 2015)



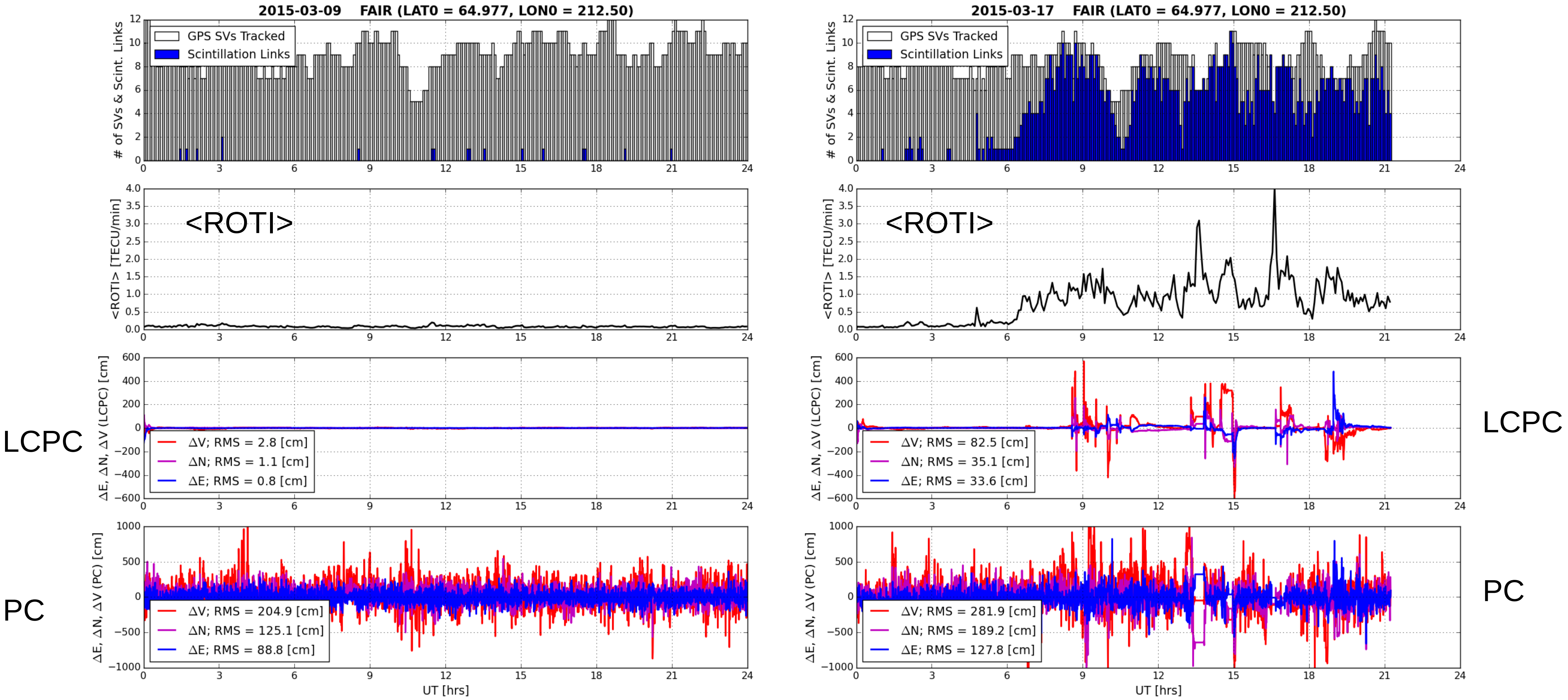
# Irregularities Expanded to Middle Latitudes during the 2015 St. Patrick's Day Storm



# Irregularities in the Polar Cap, Auroral Zone, and Low Latitudes
## during the 17 March 2015 Storm

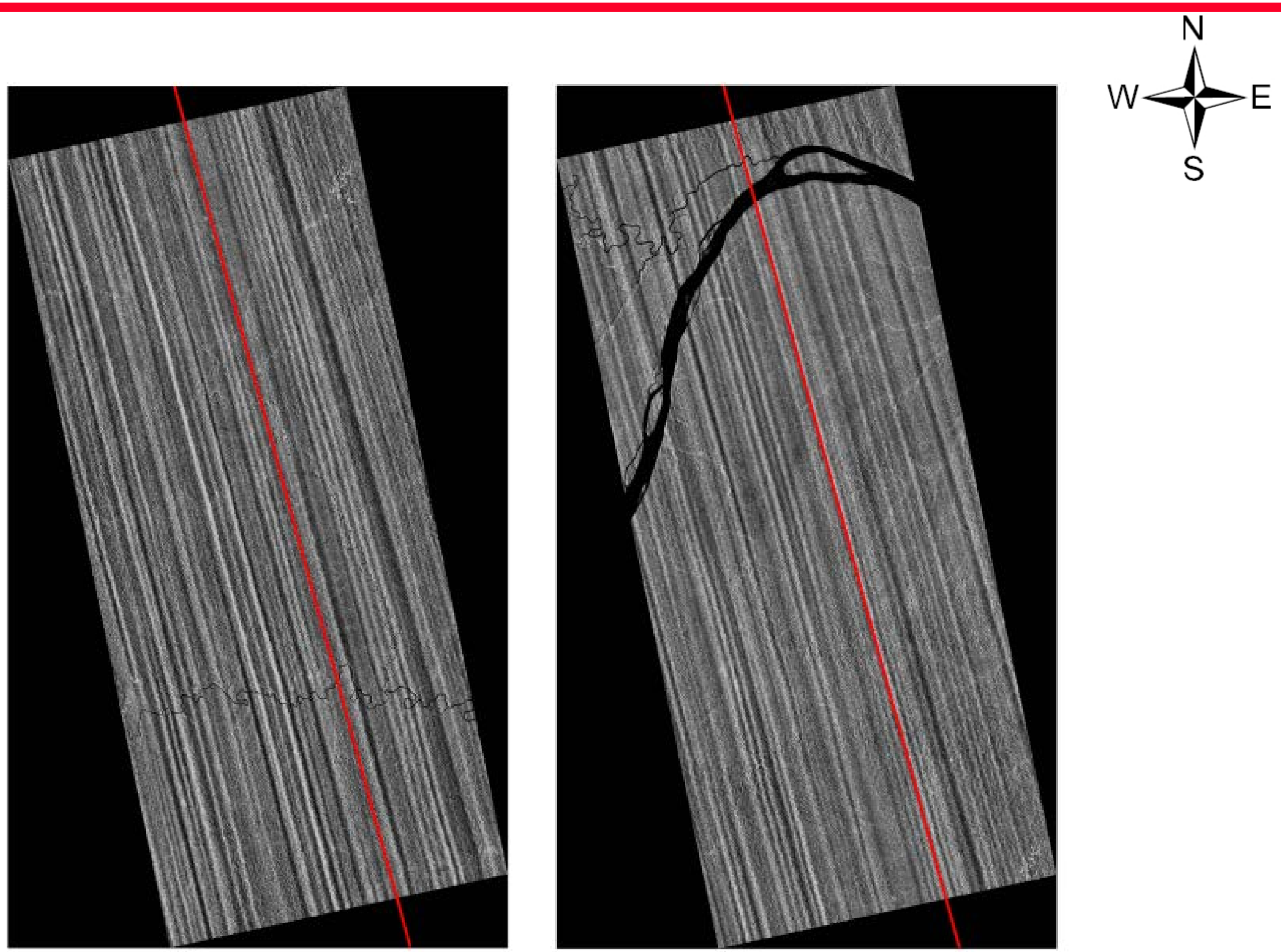


# Comparison of Positioning Errors between Quiet & Perturbed Space Weather Conditions

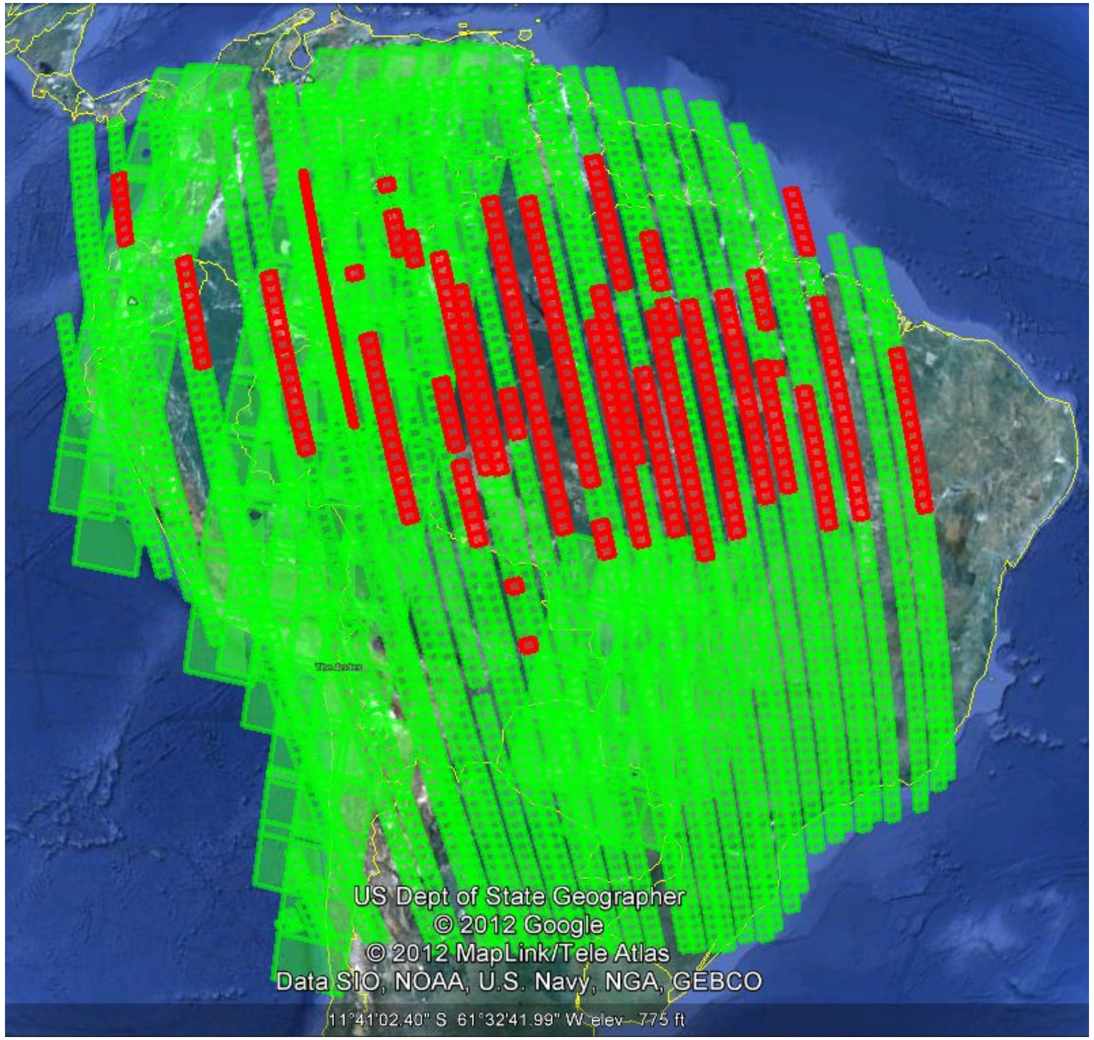


# Contamination of ALOS PALSAR Images due to Ionospheric scintillation

- Examples of geocoded PALSAR images over a South America low-latitude region near (2°S, 290°E) at about 03:19 UT on October 31, 2010.
- The red lines indicate the orientation of the ambient geomagnetic field ($B_0$).
- Streaks appear periodically in the direction $\perp B_0$ and spaced at ~km to sub-kilometer.
- Effects are identified as due to ionospheric scintillation



# A Survey of Contaminated SAR Images over South America

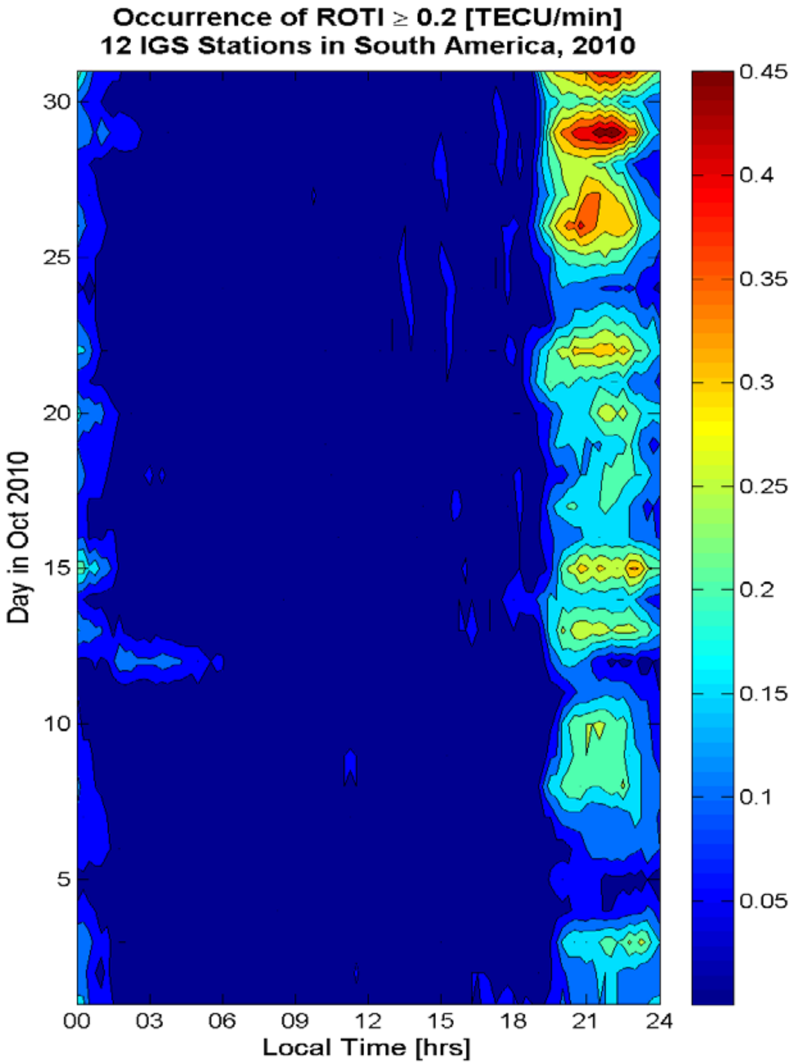



A survey of SAR image artifacts

- Period: Oct 2010
- Total images: 2779
- Artifacts seen in
  - 14% of images
  - 74% of days in the month
- Only appear in images in ascending paths (10 PM) at low-latitudes

# Correlation between SAR artifacts and GPS Measured scintillation

**GPS measure-ments**




Days in October 2012 when the streak artifacts are not seen in PALSAR images over South America.

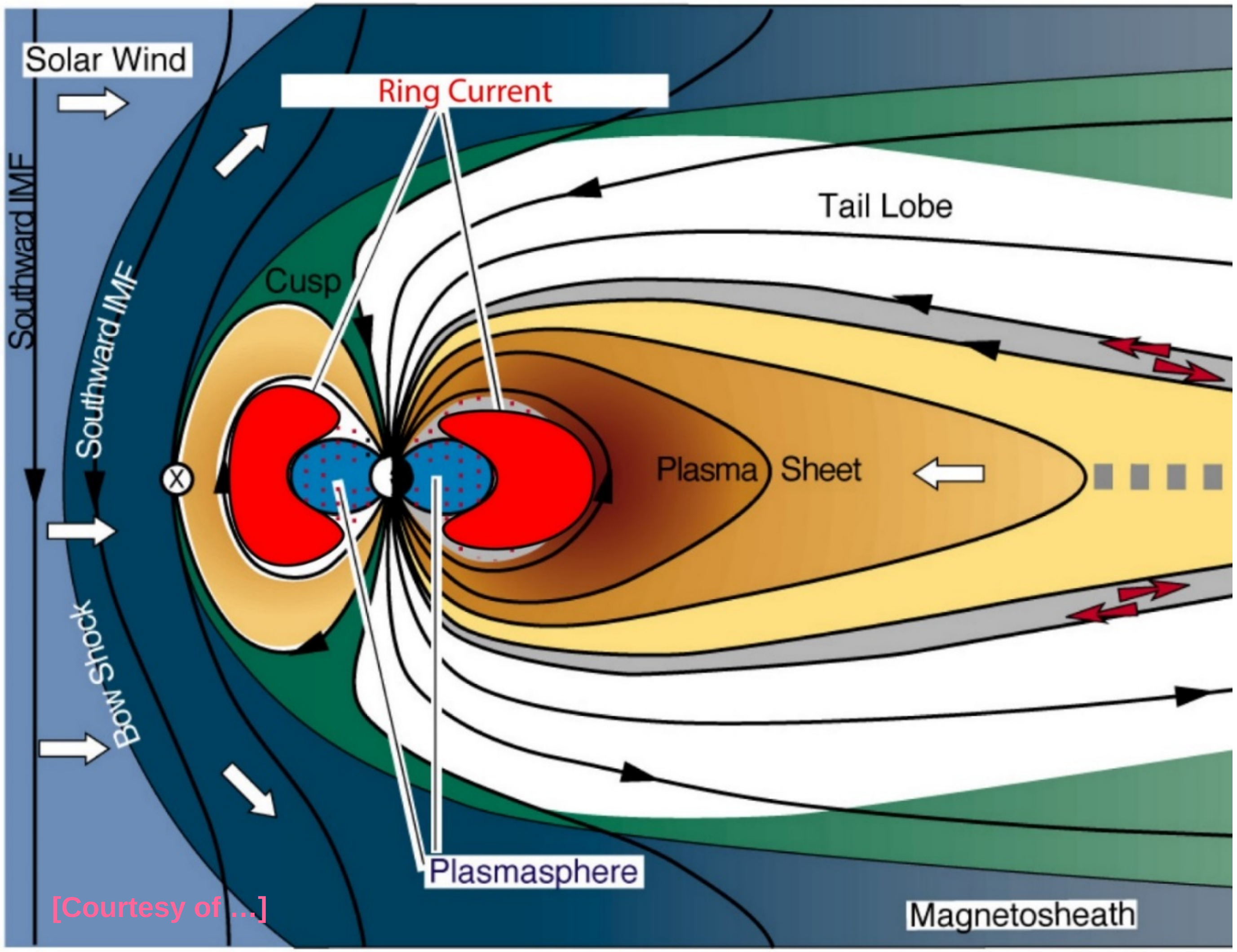
**SAR measure-ments**

| Day | 05 | 06 | 11 | 12 | 14 | 19 | 24 | 30 |
|---|---|---|---|---|---|---|---|---|
| # of images collected | 61 | 75 | 10 | 51 | 78 | 79 | 127 | 20 |

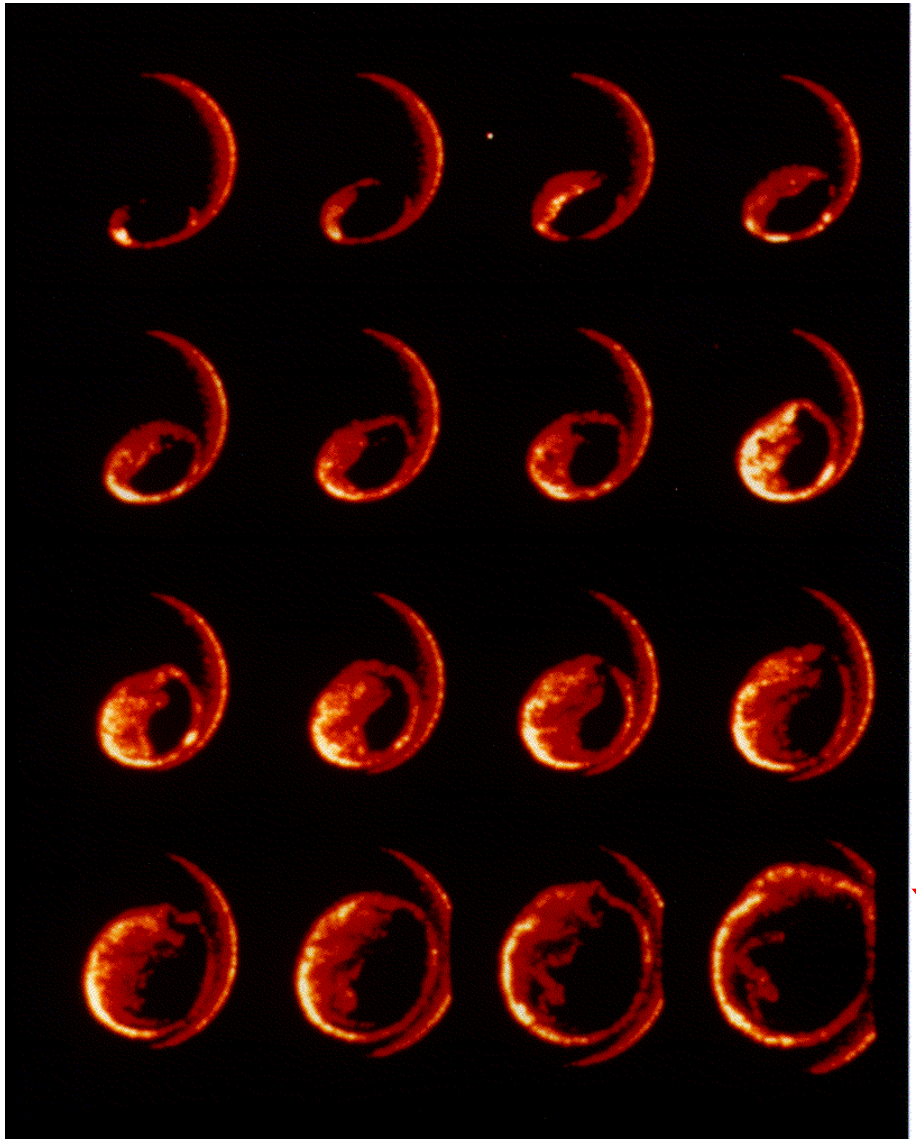
- The streak artifacts in SAR images are not seen when scintillation is not present
- Scintillation occurs exclusively during evening and night hours at low latitudes
- (ALOS-2 orbit: 12AM/12PM)

# Interactions between Ring Current and Plasmasphere

- Ring current region expands into the plasmasphere
- Interactions between the ring current & plasmasphere:
  - ✓ Auroral oval expansion
  - ✓ Stable auroral red (SAR) arc or the mid-lat trough shifted to lower latitudes
  - ✓ Electrodynamical perturbations: SAPS/SED, **E** penetration → lat gradient in **E**, Kelvin-Helmholtz instabilities → plasma blobs, undulations etc.
  - ✓ MIDLIIS



# Auroral Oval Expansion & Ring Current Enhancement



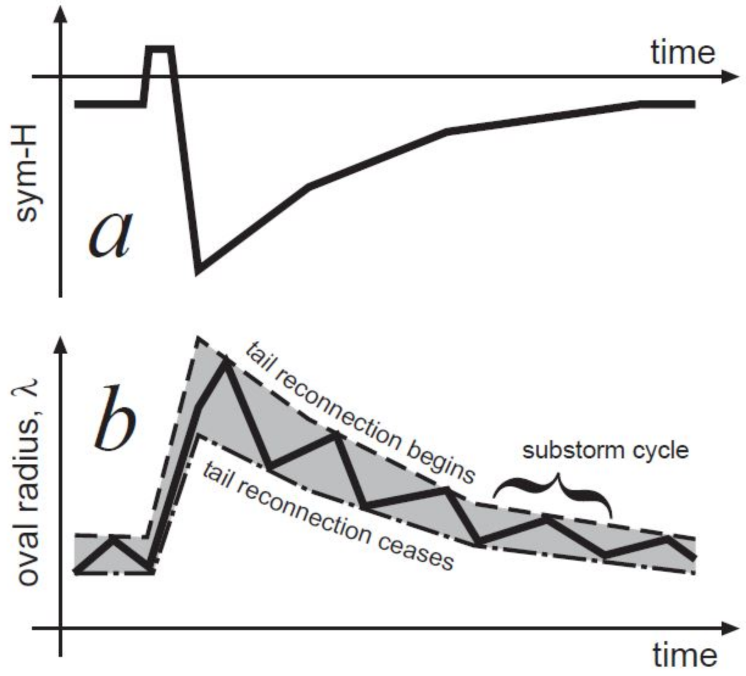
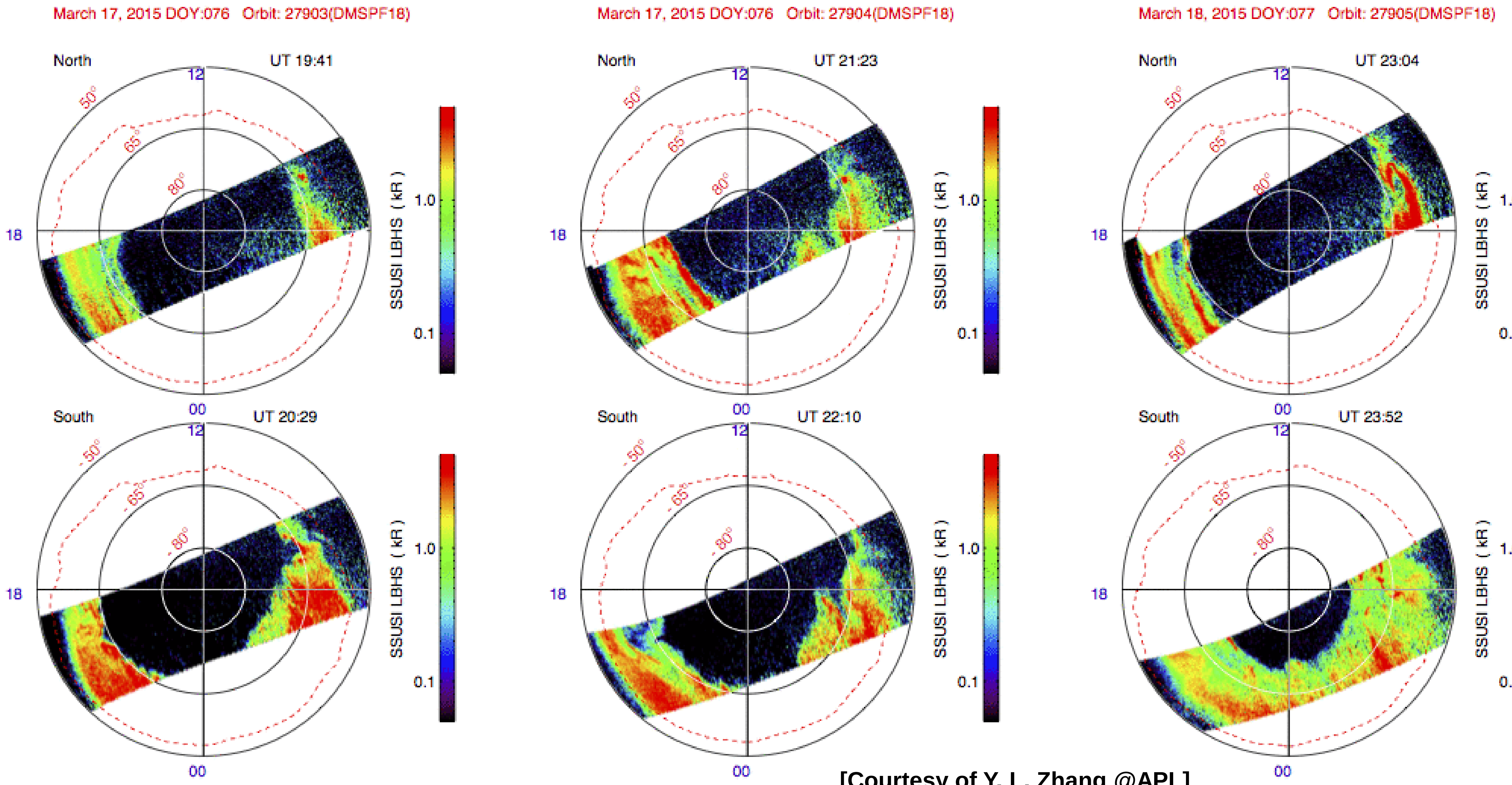



IMAGE data analysis by [Milan et al. 2009]: IMF $B_z < 0$

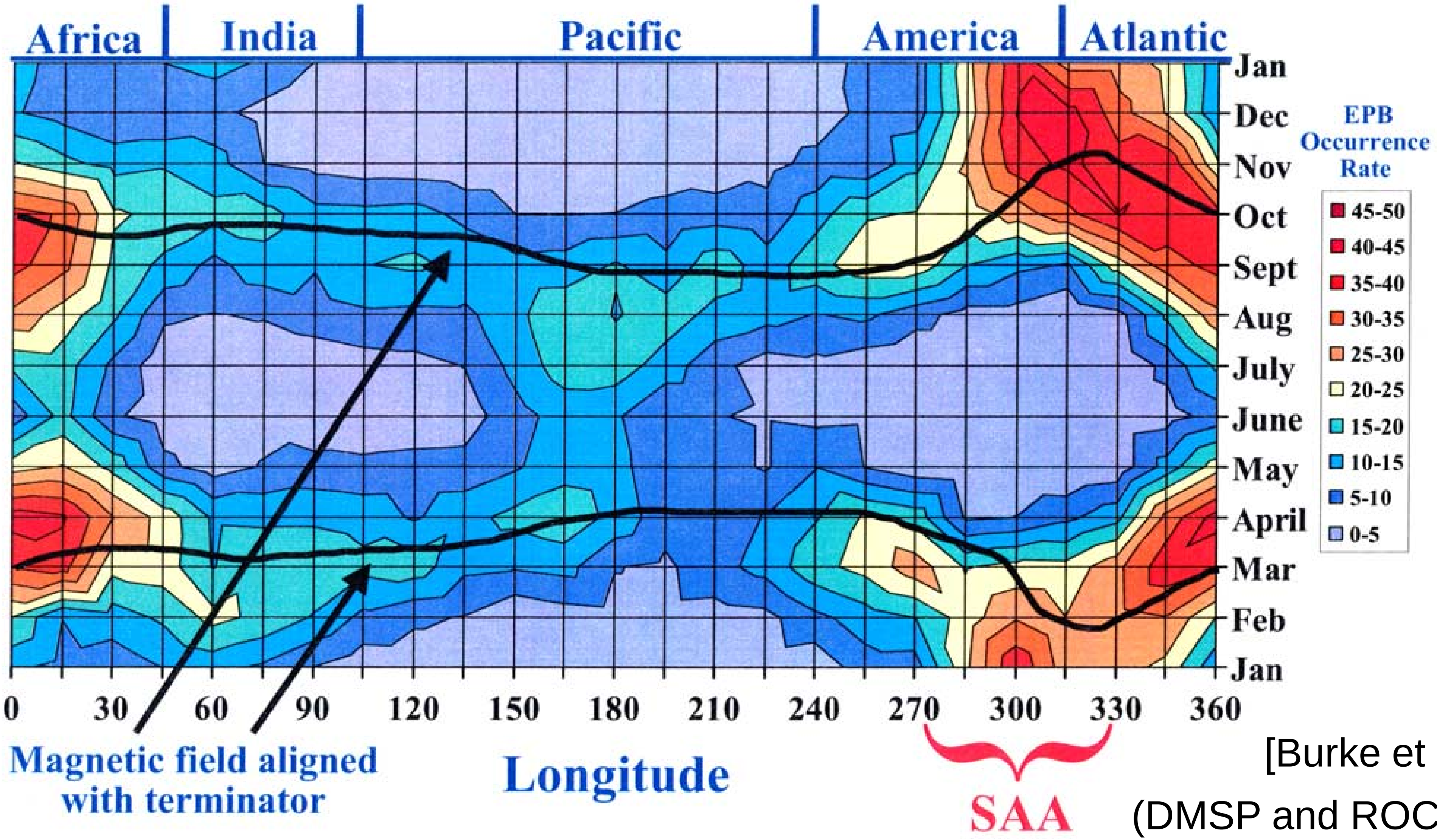
DE-1 Image Data:
136-165 nm passband of the optical filter

# DMSP Auroral Images




[Courtesy of Y. L. Zhang @APL]

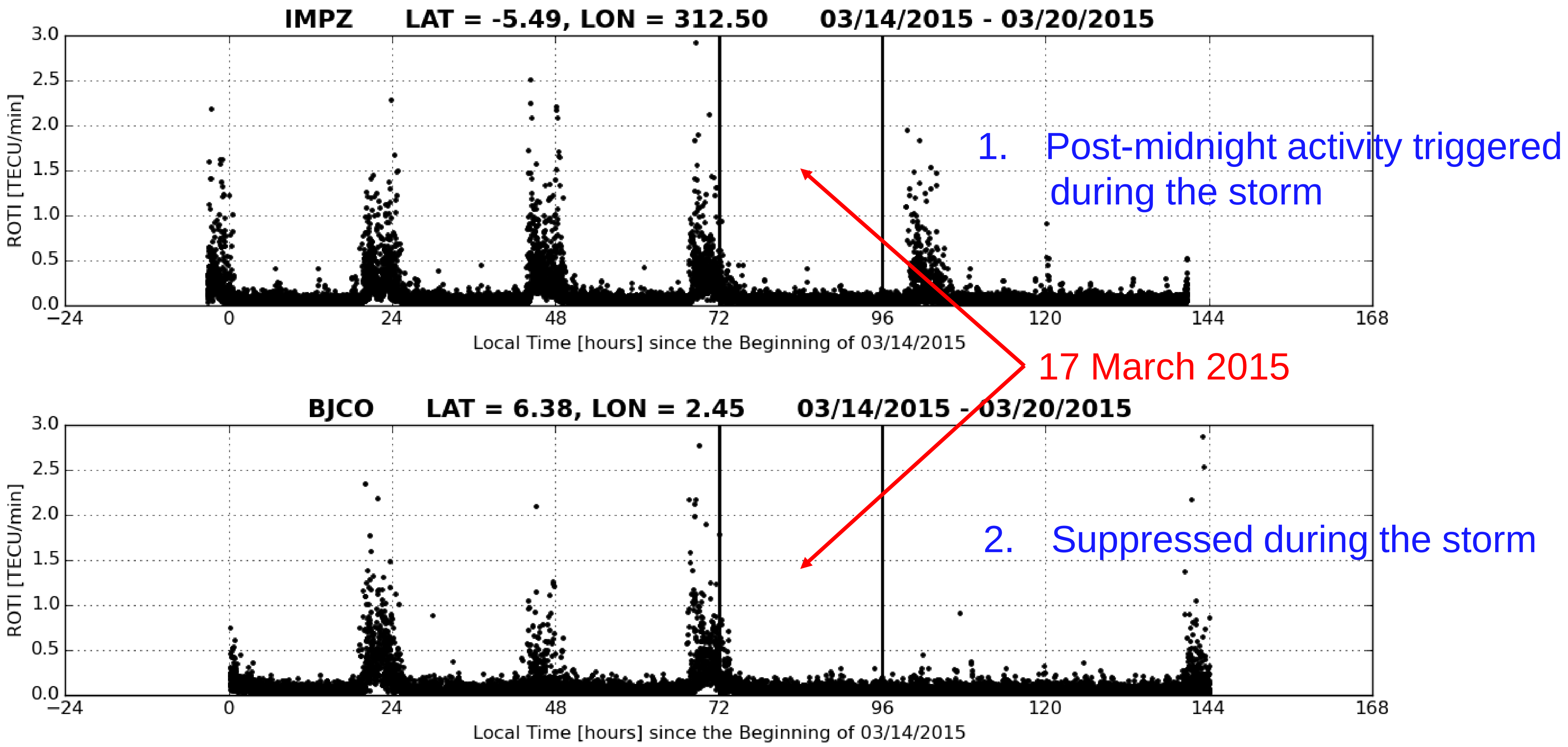
# Longitudinal Variability of Low-Latitude Irregularities: Climatology



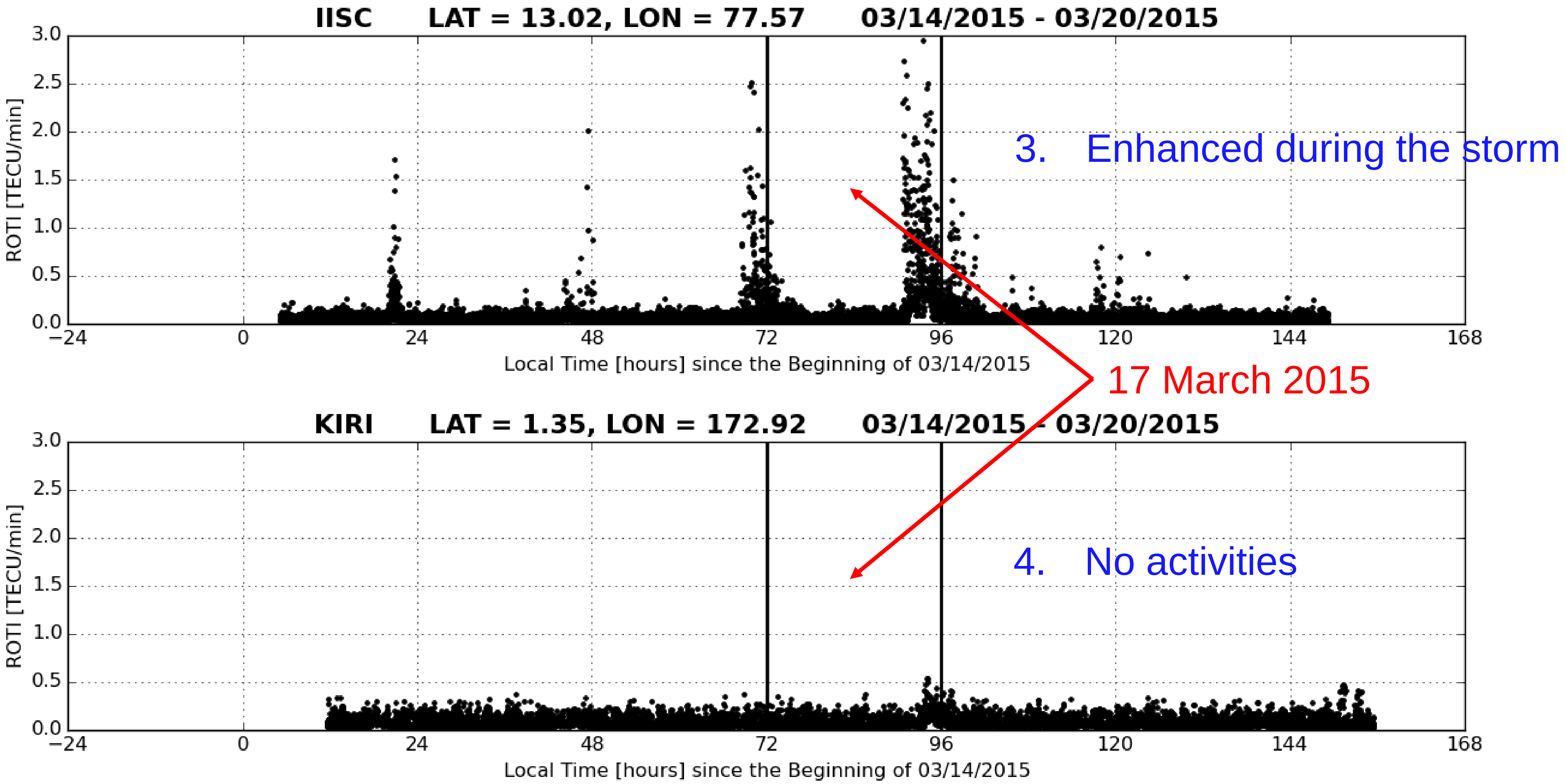

[Burke et al., 2004]

(DMSP and ROCSAT-1 Data)

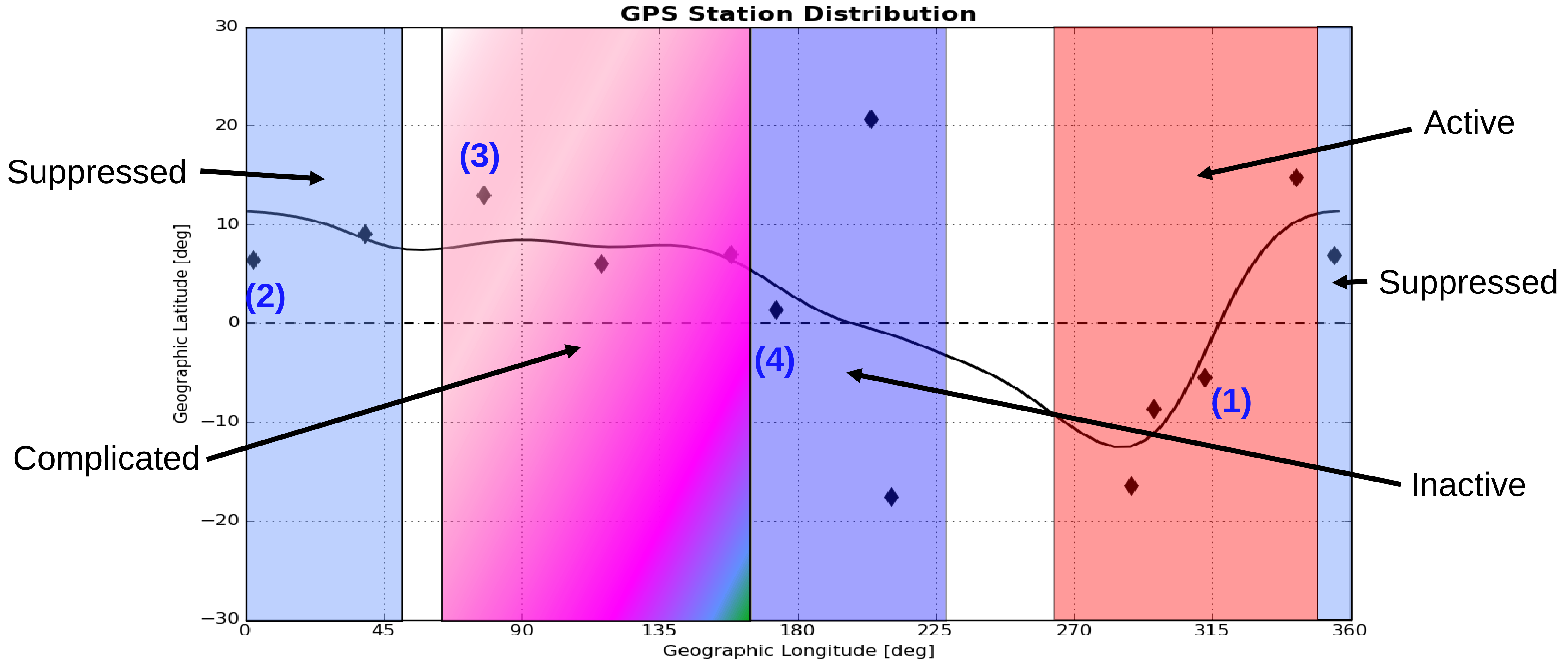
# Impact of Space Weather on Low-Latitude Irregularities
## Longitudinal Difference



# Impact of Space Weather on Low-Latitude Irregularities
## Longitudinal Difference



# Global Irregularity Activities at Low-Latitudes



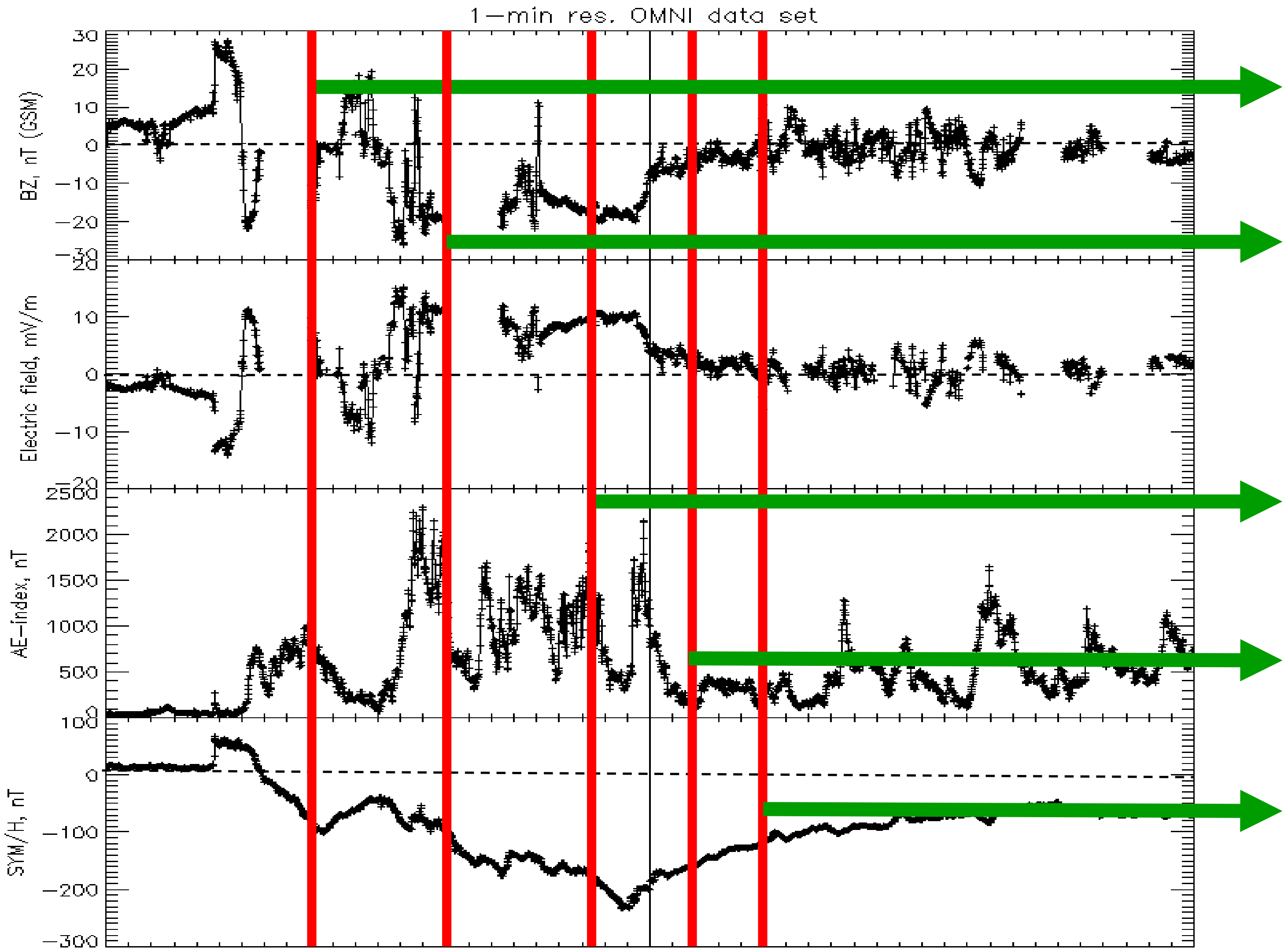
# Space Weather Conditions and Longitudinal Variations of Low-Latitude Irregularities

$B_z$

$E_y$

AE

SYM-H




17 March 2015 18 March 2015

- Pacific sector → in active
- West Asian evening sector → active; east Asian post-midnight sector → active
- European/African sector suppressed
- American evening sector → active
- American sector post-midnight → active

# Growth Rate of Plasma Rayleigh-Taylor Instability and Driving Dynamics

Localized R-T instability growth rate:

$$\gamma_{GD} = \left[\frac{c\mathbf{E} \times \mathbf{B}}{B^2} - \mathbf{U}_n - \frac{\mathbf{g}}{\nu_{in}}\right] \cdot \frac{\nabla\Sigma_{p_2}}{\Sigma_{p_1} + \Sigma_{p_2} + \Sigma_{p_3}}\left(\frac{\nabla n}{n}\right)$$

[Zalesak et al., 1988]

Fluxtube-integrated R-T instability growth rate:

$$\gamma_{RT} = \frac{\tilde{\Sigma}^F_{P,0}}{\tilde{\Sigma}^E_{P,0} + \tilde{\Sigma}^F_{P,0}}\left(V_p - U^P_L - \frac{g_e}{\nu^F_{eff}}\right) K^F - R_T$$

[Haerendel, 1973;
Haerendel et al., 1992;
Mendillo et al., 1992;
Sultan, 1996]

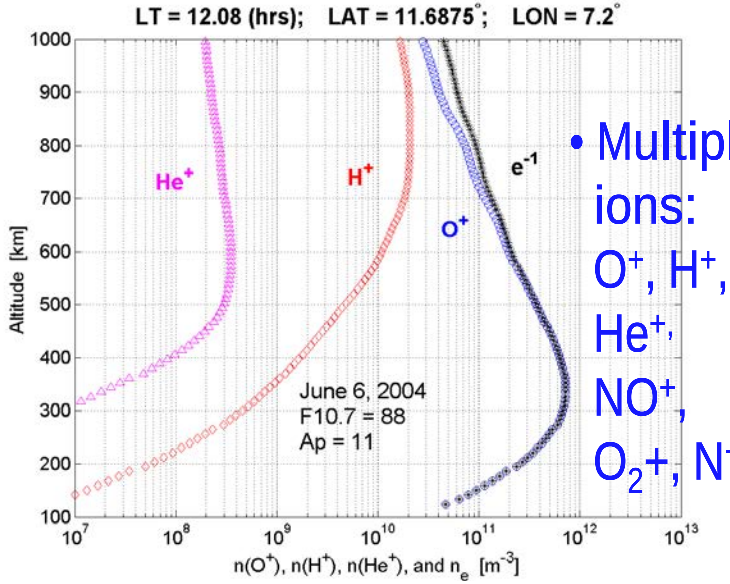
Enhanced Vp (upward plasma drift, or eastward electric field):

— Enhanced (and widened) equatorial ionospheric anomaly (EIA)

Enhanced equatorward wind, or westward E-field:

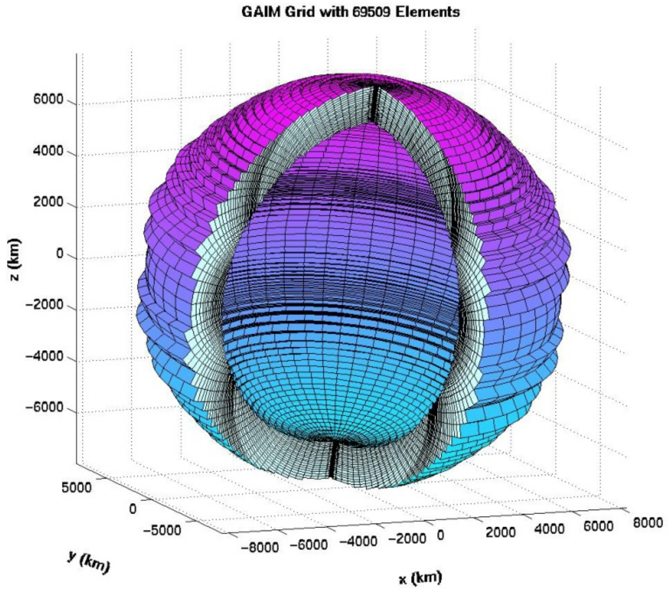
— Reduced or depleted EIA

# Global Assimilative Ionospheric Model (GAIM) to Reproduce Large-Scale Variations



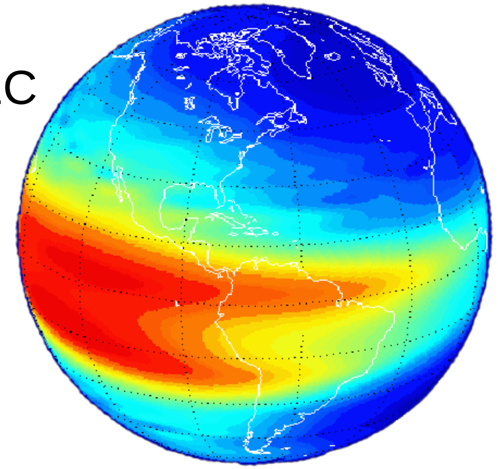

- Multiple ions: $O^+$, $H^+$, $He^+$, $NO^+$, $O_2$+, $N^+$

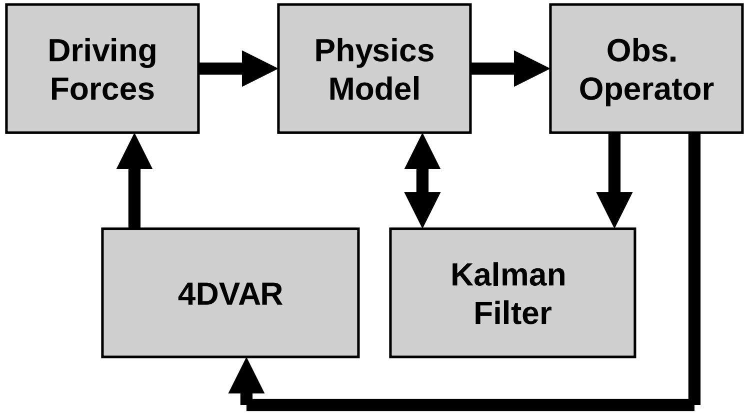
- Time dependent
- 3D grid in a magnetic frame




- Numerically solving plasma continuity and momentum equations
- Finite volume on a fixed Eulerian grid
- Hybrid explicit-implicit time integration scheme

TEC






**Assimilative Modeling**

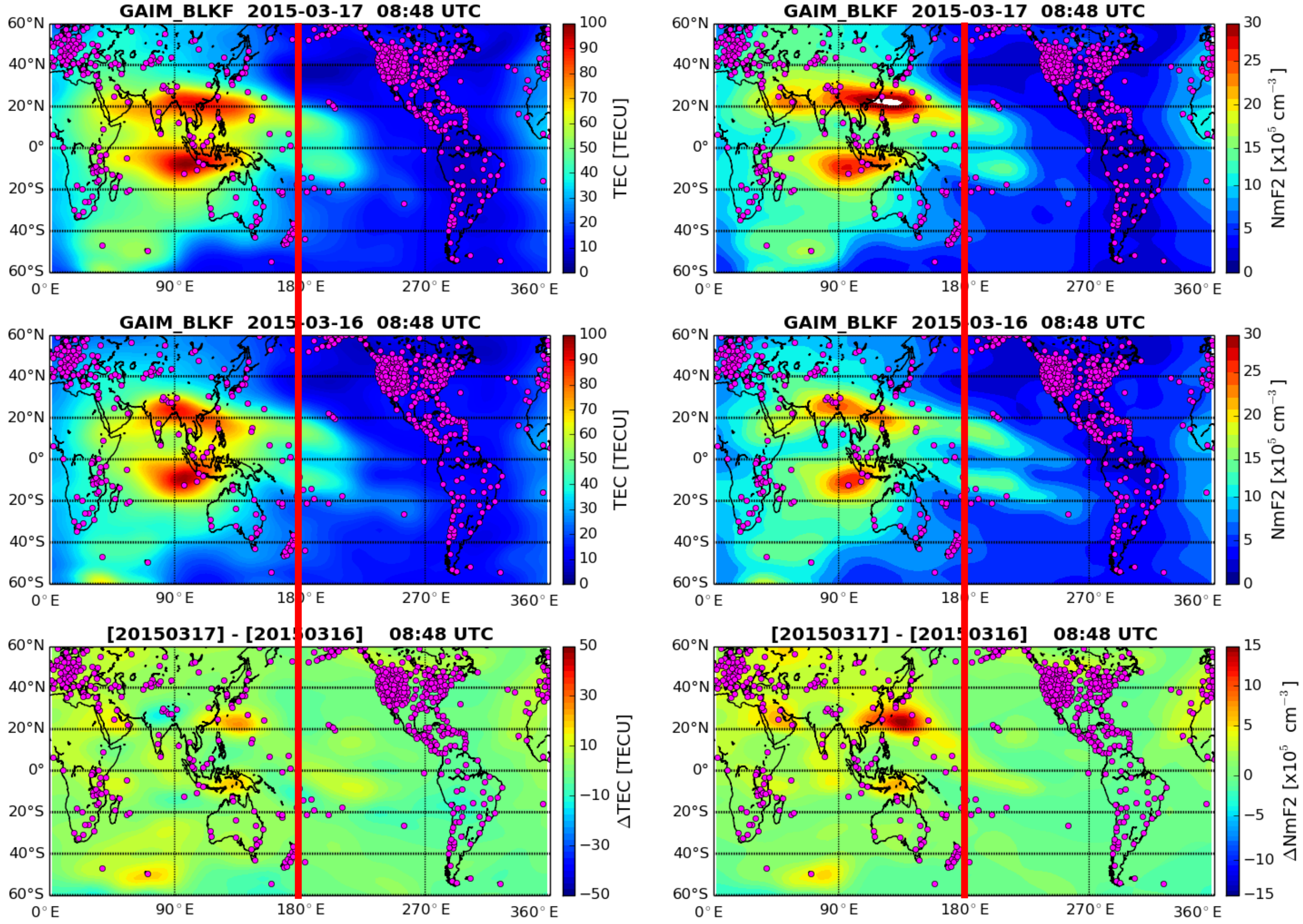
- GAIM++
  - ✓ C++ code
  - ✓ Multiple ion with plasmasphere
  - ✓ Nested grid
  - ✓ Improved magnetic field model

# EIA Is Present in the Evening Sector (Pacific)
# (Where Irregularities Are Inactive)

03-17-2015
TEC (storm)

03-16-2015
TEC (quiet)

ΔTEC




03-17-2015
$n_mF_2$ (storm)

03-16-2015
$n_mF_2$ (quiet)

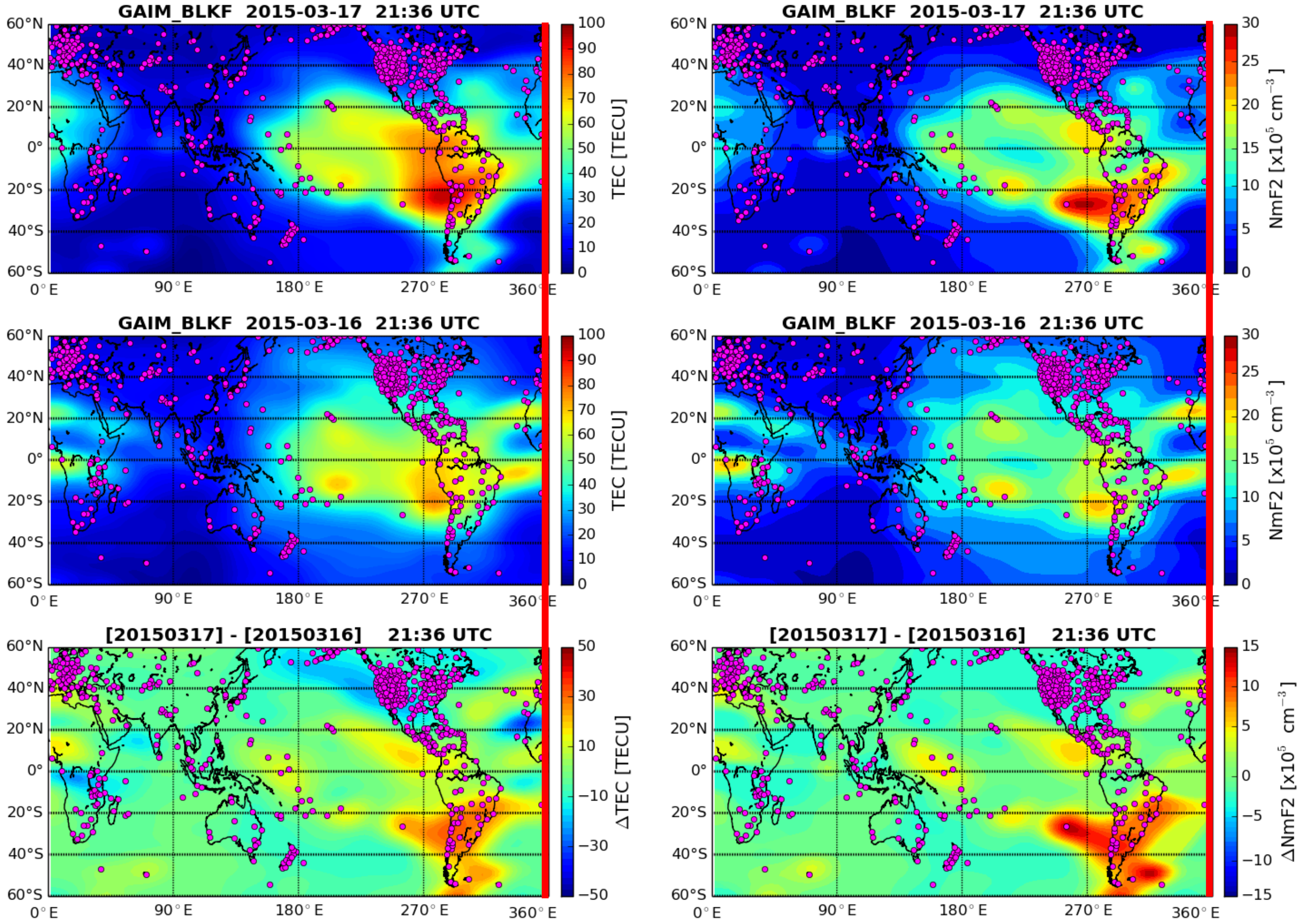
$\Delta n_mF_2$

# EIA Diminishes in the Evening Sector (Europe/Africa) (Where Irregularities Are Suppressed)

03-17-2015
TEC (storm)

03-16-2015
TEC (quiet)

ΔTEC




03-17-2015
$n_mF_2$ (storm)

03-16-2015
$n_mF_2$ (quiet)

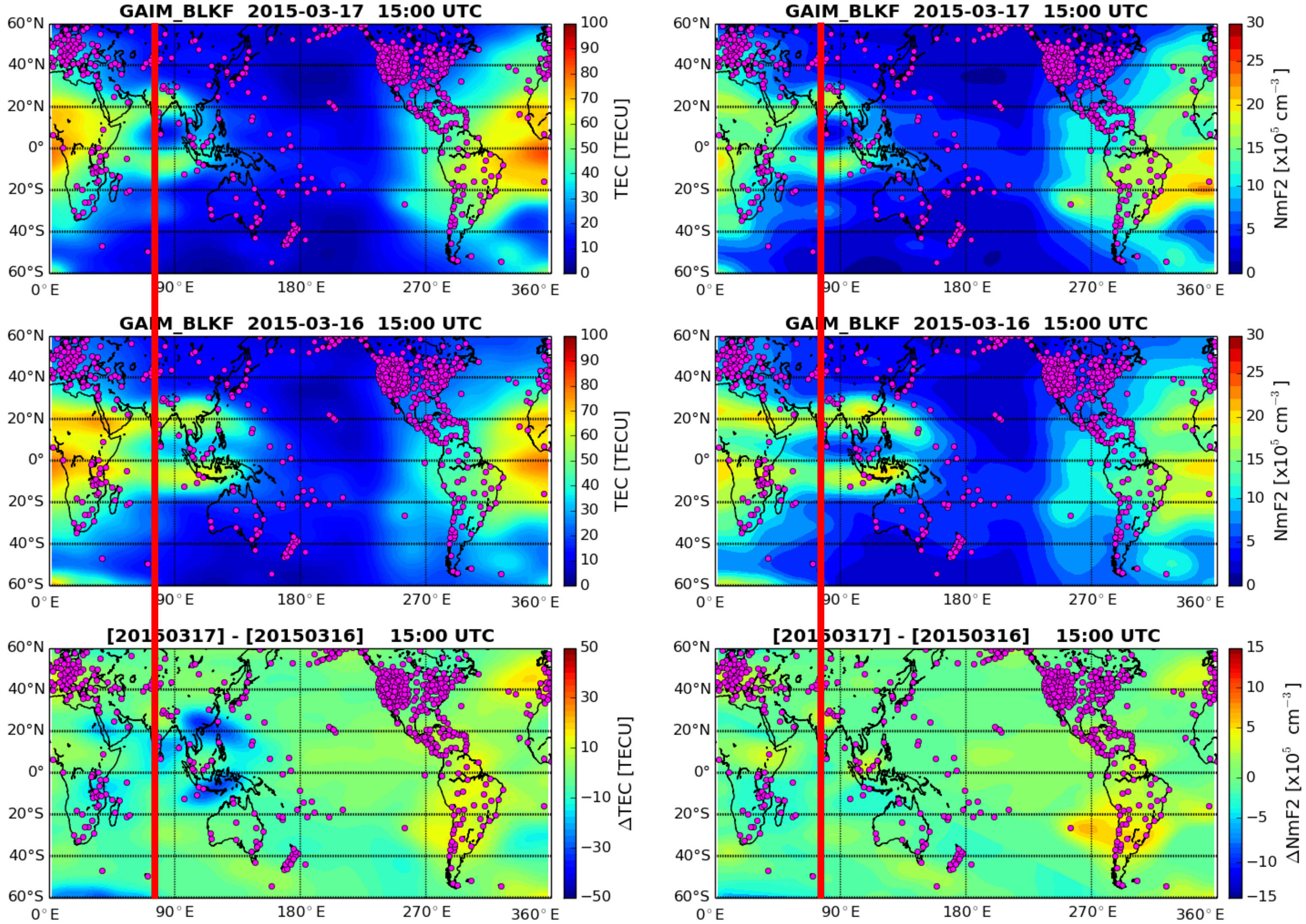
$\Delta n_mF_2$

# EIA Enhances in the Evening Sector (Asia)
# (Where Irregularities Are Present)

03-17-2015
TEC (storm)

03-16-2015
TEC (quiet)

ΔTEC




03-17-2015
$n_mF_2$ (storm)

03-16-2015
$n_mF_2$ (quiet)

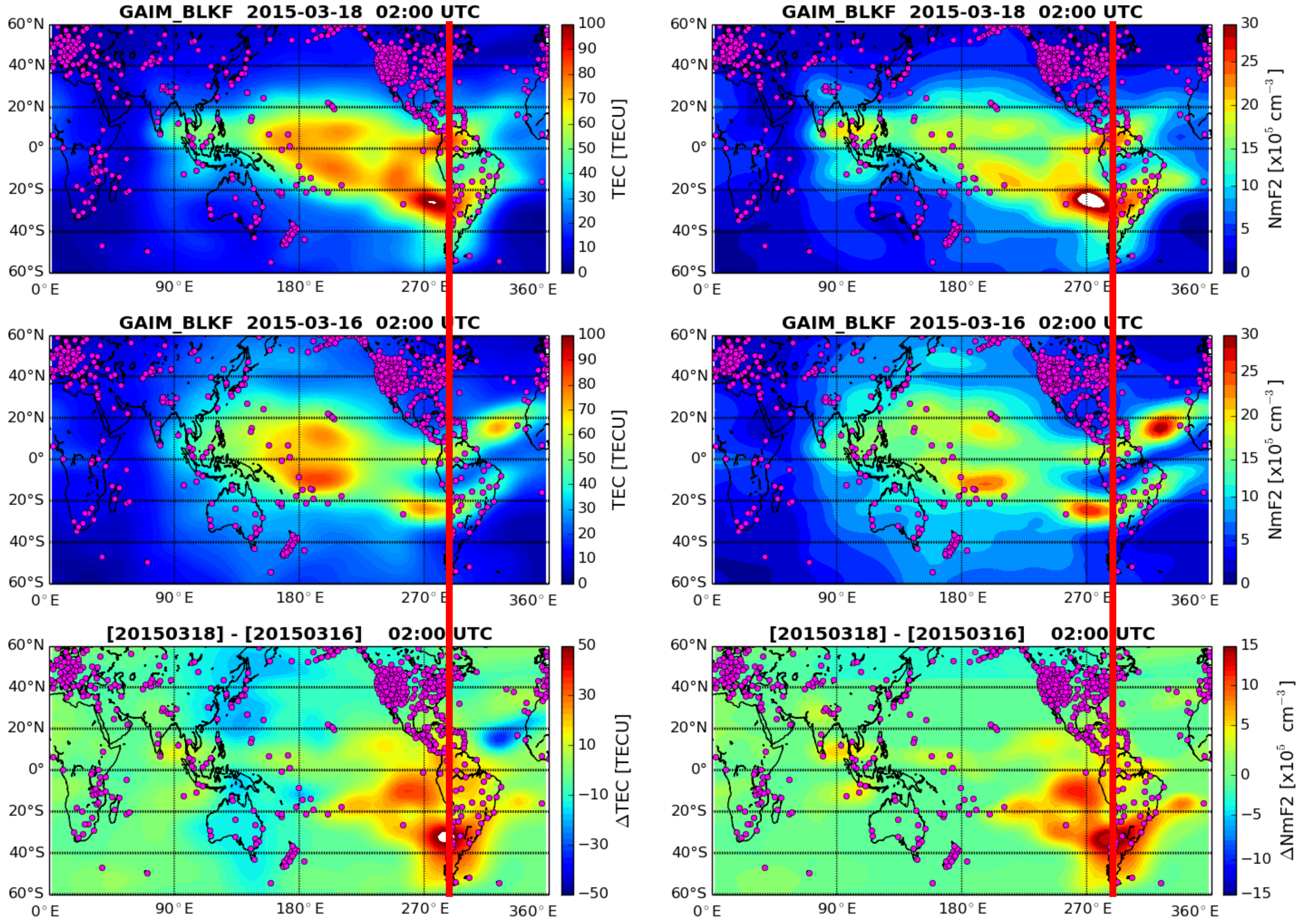
$\Delta n_mF_2$

# EIA Enhances in the Evening Sector (America)
# (Where Irregularities Are Present)

03-18-2015
TEC (storm)

03-16-2015
TEC (quiet)

ΔTEC




03-18-2015
$n_mF_2$ (storm)

03-16-2015
$n_mF_2$ (quiet)

$\Delta n_mF_2$

# EIA Enhances in the Post-Midnight Sector (America)
## (Where Irregularities Are Present)

03-18-2015
TEC (storm)

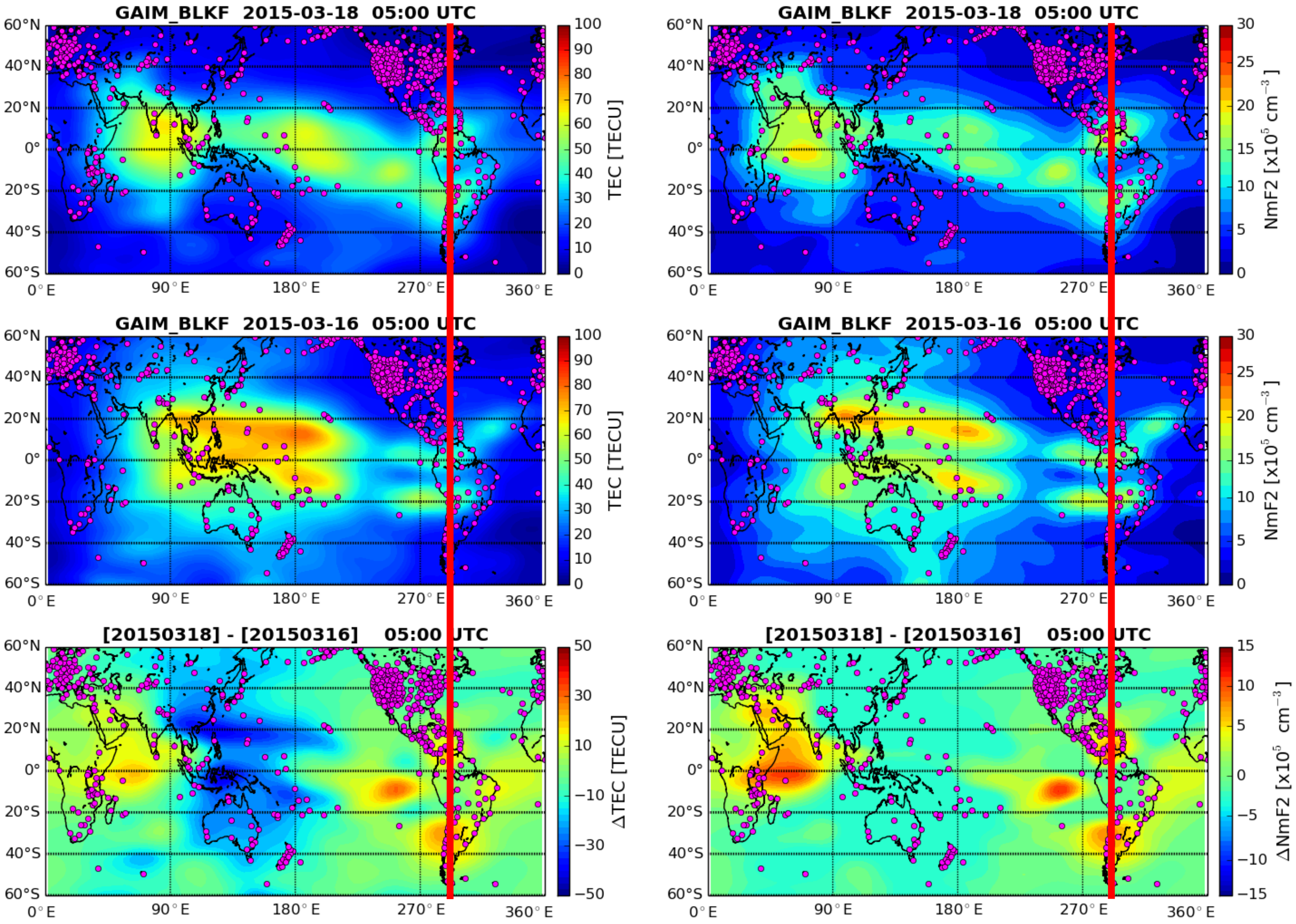
03-18-2015
$n_mF_2$ (storm)

03-16-2015
TEC (quiet)

03-16-2015
$n_mF_2$ (quiet)

ΔTEC

$\Delta n_mF_2$



# A Path to Prediction

- **Characterizing large-scale ionospheric variations under various space weather conditions**
- **Understanding their relationship with electrodynamical and thermospheric dynamical perturbations**
- **Establishing the relationship between large-scale ionospheric variations and occurrence of small-scale ionospheric irregularities**
- **Predicting the dynamical and large-scale ionospheric disturbances and then occurrence of small-scale irregularities**
- **Approaches**
  - ✓ GNSS and other ionospheric for small-scale irregularities
  - ✓ Electrodynamical and thermospheric measurements for dynamics
  - ✓ Global Assimilative Ionospheric Model for ionospheric state and dynamics
  - ✓ ITM coupled model for dynamics
  - ✓ Validation
  - ✓ Data driven techniques through machine learning with long-term existing global GNSS data

# Conclusions

- **Impact of ionospheric scintillation on GNSS and InSAR applications has been observed in GNSS positioning applications and InSAR imagery**
- **Irregularities can be triggered, enhanced, or suppressed under perturbed space weather conditions in the polar, mid-latitude, or low-latitude regions**
- **There exist relationships between large-scale ionospheric variations and occurrence of small-scale ionospheric irregularities, and the relationships can help identify ambient ionospheric conditions and underline dynamical effects that trigger, enhance, or suppress ionospheric irregularities**
- **Characterization of the relationship between large- and small-scale variations can help understand the mechanisms of irregularity development**
- **Prediction of ionospheric irregularities and scintillation can benefit from modeling large-scale variations and observations of small-scale irregularities**